Fe K EMISSION LINES IN LOW-LUMINOSITY AGNS

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We present the results of a systematic analysis of Fe K emission lines in low-luminosity AGNs (LLAGNs) observed with *ASCA*. We used a sample of LLAGNs with small intrinsic absorption to compare with luminous AGNs and accretion models. Some objects show an Fe line at 6.4 keV or 6.7 keV, and the rest of the objects show no significant Fe K emission line. We made a composite spectrum of sources without detected Fe emission lines to search for weak lines and obtained an upper limit on the equivalent width (EW) of a narrow line at 6.4 keV of 145 eV, which is marginally consistent with EWs seen in Seyfert 1s. Even in those objects with detected Fe lines, a skewed broad component, typically observed in Seyfert 1s, is not seen. The weakness of the Fe line is consistent with the absence of an optically thick disk in the vicinity of a central black hole. Alternatively, it might be due to the ionization of a standard disk. The lack of big blue bump favors the former.

1. Introduction

Optical spectroscopic surveys have shown that more than one third of nearby galaxies harbor low-luminosity AGNs (LLAGNs; [1]). Their bolometric luminosities ($L_{\rm bol} < 10^{42}$ ergs s^{-1}) and the black hole masses measured dynamically indicate that LLAGNs are radiating at an extremely low Eddington ratio, typically $L/L_{\rm Edd} \approx 10^{-3} - 10^{-6}$. Models of low-radiative efficiency accretion flows such as advection-dominated accretion flows (ADAFs) have been developed and applied to LLAGNs (e.g., [2]).

Fe K emission lines are a powerful diagnostic tool to probe the inner parts of accretion disks. In the ADAF scenario, the inner parts of the disk are almost fully ionized, and no Fe K emission line is expected. On the other hand, if an optically thick standard disk is present, a fluorescent line is produced. In this paper, we summarize *ASCA* results on Fe K lines and give constraints on accretion disks in LLAGNs.

2. The Sample

We systematically analyzed 52 *ASCA* observations of 21 LINERs (low-lonization nuclear emission-line regions) and 17 low-luminosity Seyferts ([3]). The sample is constructed primarily based on the classification of the Palomar survey ([1]), with several other objects added. We made a subsample of LLAGNs from this sample by choosing objects whose hard X-ray emission is dominated by the nucleus, by using X-ray variability, spectra, images, and X-ray to optical emission ratios to judge whether the AGN contribution dominates ([4]). Highly absorbed objects are excluded since they are not suitable for studying accretion disks because of the complicated Fe K emission expected from sources other sources. The final sample consists of 14 observations of 13 LLAGNs. The basic data of the galaxies in our sample are shown in Table 1.

3. Results

The X-ray spectra of LLAGNs are well fitted by a canonical model that consists of a power law (photon index $\Gamma \approx 1.8$) and a Raymond-Smith thermal plasma with $kT \approx 0.6$ keV. The thermal component was not required in five objects (NGC 3147, 3998, 4203, 4639, and 5033), but the other objects in the present sample were well described by the canonical model. Fe K emission is detected in seven out of 13 objects. The line center energy, line width, and equivalent width (EW) are summarized in Table 2. For objects without significant Fe K emission, the line center energy was

Table 1

The Sample

Name	Class	Distance	L_X [a]	L_X/L_{Edd}
NGC 315	L1.9	65.8	49	...
NGC 1097	L/S1.5	14.5	5.2	4.6×10^{-6}
NGC 3031	S1.5	1.4	0.43	2.0×10^{-7}
NGC 3147	S2	40.9	34	3.4×10^{-6}
NGC 3998	L1.9	21.6	46	6.5×10^{-6}
NGC 4203	L1.9	9.7	2.3	9.3×10^{-5}
NGC 4261	L2	35.1	15	2.3×10^{-6}
NGC 4450	L1.9	16.8	2.2	1.8×10^{-6}
NGC 4579[b]	S/L1.9	16.8	14	2.3×10^{-6}
NGC 4579[c]			20	3.2×10^{-6}
NGC 4594	L2	20.0	14	1.0×10^{-6}
NGC 4639	S1.0	16.8	3.6	...
NGC 5005	L1.9	21.3	3.8	...
NGC 5033	S1.5	18.7	23	6.1×10^{-5}

a: luminosity in 2–10 keV band in units of 10^{40} ergs s^{-1}; *b*: observed in 1995; *c*: observed in 1998

fixed at 6.4 keV in the source rest frame and upper limits on EW were calculated. The line center energies in three objects (NGC 3147, 3998, and 5033) are 6.4 keV, which is expected from cold (or low-ionization state) Fe, while two objects (NGC 4261 and 4639) have higher energies (~ 6.7 keV), consistent with He-like Fe. Although the center energy of the Fe line in NGC 3031 (M81) is consistent with both cold and highly ionized Fe, other observations of NGC 3031 indicate a higher line centroid energy ([5]). NGC 4579 was observed more than twice. The line center energy in this object decreased from 6.7 keV to 6.4 keV, accompanied by an increase of the continuum luminosity by 35%. We note that the emission lines at 6.7 keV most likely originate from an AGN, particularly in the case of NGC 3031 ([5]) and NGC 4579 ([6, 7]), and a thermal origin is unlikely because the continuum of NGC 3031 has a power-law shape and the Fe line in NGC 4579 is variable.

Thus, Fe line energies in LLAGNs shows some diversity compared to luminous Seyferts, in which the line is generally peaked at 6.4 keV. No broad, asymmetric Fe lines such as those seen in classical Seyfert 1s are detected in LLAGNs (e.g., [6, 8]), although the photon statistics are limited.

The upper limits on EW are not very tight for the objects without significant Fe lines. In order to obtain tighter constraints, we made a composite spectrum. We coadded the spectra of six objects (NGC 315, 1097, 4203, 4450, 4594, and 4639) from which Fe lines are not detected or only marginally detected. All of these have very similar continuum slopes. NGC 5005 was not used because its spectral slope is flatter than others. The composite spectrum, shown in Figure 1, is well fitted by the canonical model and no Fe line is required. The upper limit to the EW of a narrow Fe line at 6.4 keV is 38^{+107}_{-38} eV. This EW is smaller than or marginally consistent with that for a core in the disk-line profile in luminous Seyfert 1s ([9]). The constraint on the EW of a broader component is weaker. For example, the EW of a Gaussian line with $\sigma = 0.2$ keV is 74^{+137}_{-74} eV. This upper limit lies on the lowest end of the distribution of Fe EWs in luminous Seyfert 1s.

The continuum of the composite spectrum is well described by a power law with a photon index of 1.64 ± 0.03; a thermal Bremsstrahlung model is not adequate. This reconfirms that the X-ray emission in the present sample is dominated by an AGN and that the contribution from discrete X-ray source such as low-mass X-ray binaries in the host galaxy is small. Therefore, the weakness of an Fe emission line is not due to dilution by sources other than an AGN; instead, it appears to be a property intrinsic to some LLAGNs.

Table 2

Results of Spectral Fits

Name	$N_{\rm H}$ (10^{20} cm^{-2})	Photon Index	Energy[a] (keV)	Width (keV)	EW (eV)
NGC 315	$0.49^{+0.41}_{-0.33}$	$1.73^{+0.28}_{-0.25}$	6.4	0	<380
NGC 1097	$0.13^{+0.10}_{-0.07}$	$1.67^{+0.09}_{-0.10}$	6.4	0	<160
NGC 3031	$0(<0.053)$	$1.796^{+0.027}_{-0.028}$	$6.59^{+0.22}_{-0.13}$	0	106^{+59}_{-56}
NGC 3147	$0.062^{+0.05}_{-0.024}$	$1.82^{+0.10}_{-0.09}$	6.49 ± 0.09	0	490^{+220}_{-230}
NGC 3998	0.082 ± 0.012	$1.90^{+0.03}_{-0.04}$	$6.41^{+0.12}_{-0.19}$	0	85^{+81}_{-71}
NGC 4203	$0.022(<0.053)$	$1.78^{+0.07}_{-0.08}$	6.4	0	<310
NGC 4261	$0.17(<0.39)$	$1.30^{+0.07}_{-0.06}$	$6.85^{+0.08}_{-0.15}$	0	550^{+300}_{-310}
NGC 4450	$0(<0.082)$	$1.75^{+0.18}_{-0.17}$	6.4	0	<1200
NGC 4579[b]	0.04 ± 0.03	1.72 ± 0.05	$6.73^{+0.13}_{-0.12}$	$0.17^{+0.11}_{-0.12}$	490^{+180}_{-190}
NGC 4579[c]	$0.04(<0.13)$	1.81 ± 0.06	6.39 ± 0.09	0 (<0.16)	250^{+105}_{-95}
NGC 4594	0.73 ± 0.29	1.89 ± 0.16	6.4	0	<150
NGC 4639	$0.069^{+0.041}_{-0.038}$	1.66 ± 0.10	$6.67^{+0.16}_{-0.23}$	0	520^{+320}_{-300}
NGC 5005	$0.10(<0.86)$	0.97 ± 0.37	6.4	0	<810
NGC 5033	0.087 ± 0.017	1.72 ± 0.04	$6.43^{+0.13}_{-0.08}$	0.08 (<0.23)	306^{+116}_{-119}

Errors are at the 90% confidence for one parameter of interest. The data without errors denote fixed parameter. *a*: The line center energy is in the source rest frame; *b*: observed in 1995; *c*: observed in 1998.

4. Discussion

We have shown that Fe emission lines are seen in some LLAGNs but that they are very weak in others. Since we targeted objects whose hard X-ray emission is most likely dominated by the nucleus, the observed properties of the X-ray spectra are attributed to the nature of LLAGNs. The observed properties (continuum shape and Fe line parameters) show no clear correlation with $L_{\rm X}$, black hole mass, and $L_{\rm X}/L_{\rm Edd}$. The continuum slope of LLAGNs are in the range $\Gamma = 1.6$–1.9, which is quite similar to those seen in luminous AGNs. These photon indices are also in agreement with the predictions of low-radiative efficiency accretion models, given the accretion rates of the present sample ($L_{\rm X}/L_{\rm Edd} \approx 10^{-6}$; see Table 1) (e.g., [12]).

The small EW of the Fe line in the composite spectrum is in accordance with the absence of an inner optically thick disk. Alternatively, the inner part of such a disk may be highly ionized.

If an optically thick standard disk is present, a broad Fe K line is expected through reprocessing by the disk. Depending on the accretion rate, the surface of the disk could be ionized by irradiation (e.g., [10]). When the disk surface is almost completely ionized to the Thomson depth, an Fe K line is no longer expected. An Fe K line can also be suppressed if the ionization state of Fe is intermediate due to resonant trapping and Auger destruction ([11]). An emission line without a broad component can be produced if the inner part of the disk is highly ionized. Thus, the observed Fe lines in LLAGNs (centered at 6.4 keV or 6.7 keV, or absent) might be understood in terms of the ionization state of the disk. There are, however, serious problems in this scenario. LLAGNs have very low luminosities and very low Eddington ratios (Table 1). It seems difficult to achieve high ionization states under these conditions.

The detected Fe lines that lack a very broad component are consistent with a scenario in which an inner optically thick disk is absent. If the inner part of the accretion disk becomes a hot ADAF, the Fe atoms should be completely ionized and no Fe emission line is expected. In this case, we might observe a fluorescent Fe line only from the outer optically thick regions of the disk, or from regions exterior to the disk (e.g., an obscuring torus presumed in the unification scheme of Seyferts). The limits on the EW of a narrow line at 6.4 keV in the composite spectrum indicate that cold matter (optically thick disk and torus) subtends only a small solid angle as viewed from the X-ray source; this is consistent with the

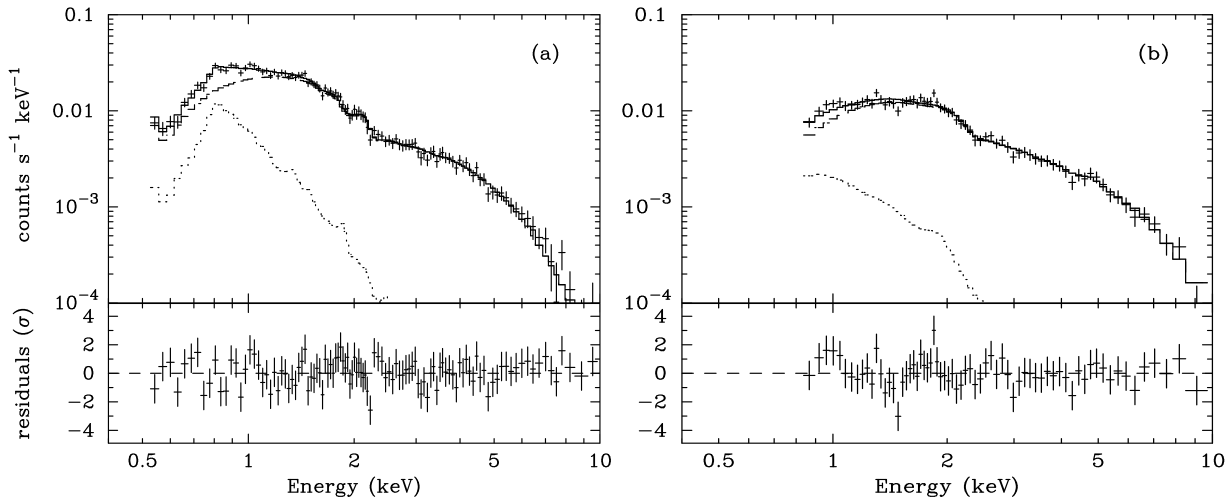

Figure 1. Composite (a) SIS and (b) GIS spectrum of six LLAGNs. Although spectral fits were done simultaneously, the figures are shown separately for clarity.

expectation. An Fe line at 6.4 keV is seen in four objects, and their relatively narrow width is also in agreement with this scenario. An additional support for the absence of an inner optically thick disk is the lack of big blue bump (BBB; [13, 14]). Note, however, that the inner temperature of an optically thick disk depends on the black hole mass and mass accretion rate. A definitive evaluation of the strength of the BBB will require accurate black hole mass measurements ([2]). Therefore, the combination of Fe K lines, spectral energy distributions, and black hole mass measurements provides a powerful diagnostic tool of accretion disks. Although the absence of Fe lines and Fe lines at 6.4 keV can be understood in a scenario invoking an ADAF plus an outer standard disk, the Fe lines at 6.7 keV are still puzzling. Future observations of Fe lines with high signal-to-noise ratio will be able to constrain the location of Fe-emitting region and the structure of accretion disks in LLAGNs.

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